# Deep-sea ferromanganese deposits and their resource potential for India

*Virupaxa K. Banakar*

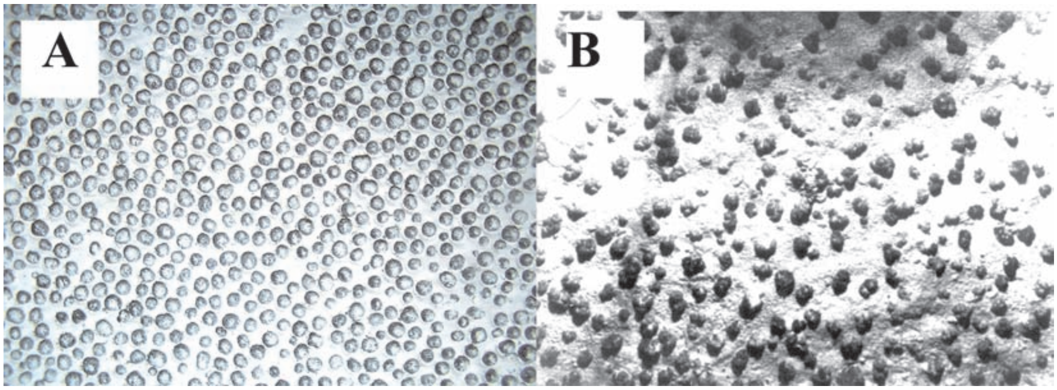
Abstract | Due to rapidly depleting land-based mineral resources, oceanic mineral deposits gain greater significance. Ferromanganese deposits on the seabed (nodules) and seamounts (crusts) known for the enrichment of several transition metals were discovered during pioneering expeditions of H. M. S. Challenger during 1872–76. The metal contents in these deposits show large variations from basin to basin. For India, the Cu and Ni (~1% each) in nodules and Co (~0.7%) and Pt (~0.5 ppm) in seamount crusts recovered from the Indian Ocean are important. The hydrogenous crusts are not only important as economically valuable deposits of Co and Pt, but also are potential paleoceanographic repositories. Ferromanganese nodule exploration by India began in 1981 and concluded with recognition by the International Seabed Authority as a Pioneer Investor in 1987. This exploration license provides India with exclusive exploration rights over an area of 150,000 km$^2$ (Pioneer Area) in the Central Indian Ocean. Nearly 700 million tonnes of nodule resources are estimated in this mine site, which are expected to contain around 14 million tonnes of combined Cu and Ni metals valued approximately over Rs. 1000 billion at current average market rate. Quantitative resource evaluation for seamount ferromanganese crusts is not yet available due to limited exploratory work. However, a promising area of Co–Pt enriched ferromanganese crust occurrence has been discovered on the Afanasiy-Nikitin Seamounts in the Eastern Equatorial Indian Ocean by NIO scientists, which contains Co upto 0.9 % and Pt upto 1 ppm.

*National Institute of Oceanography (CSIR), Dona Paula, Goa-403 004, India.*
*banakar@nio.org*

## Introduction

The economic importance of marine ferromanganese deposits became evident when Mero (1965) recognized enrichment of transition metals such as copper (Cu), nickel (Ni), iron (Fe) and manganese (Mn) in ferromanganese nodules (FMN) (Figure 1). Subsequent publications by Halbach et al. (1982), Manheim (1986), and Hein et al. (1987) showed enrichment of cobalt (Co) in ferromanganese crusts (FMC) recovered from Pacific seamounts (Figure 2). A tentative estimation indicates that ~3 trillion tons of FMNs are spread over the deep-seafloor and ~200 billion tonnes of FMCs occur on the seamounts of the world oceans (Hein et al., 2003). The formation of the FMNs is the result of a combination of hydrogenous and diagenetic accretion of the metal-hydroxides around any hard nucleus, whereas, seamount crusts are the result of hydrogenous or mixed hydrogenous–hydrothermal precipitation of colloidal metal hydroxides over seamount rock substrates (Hein et al., 1987). The mixed crusts normally do not strongly enrich transition metals

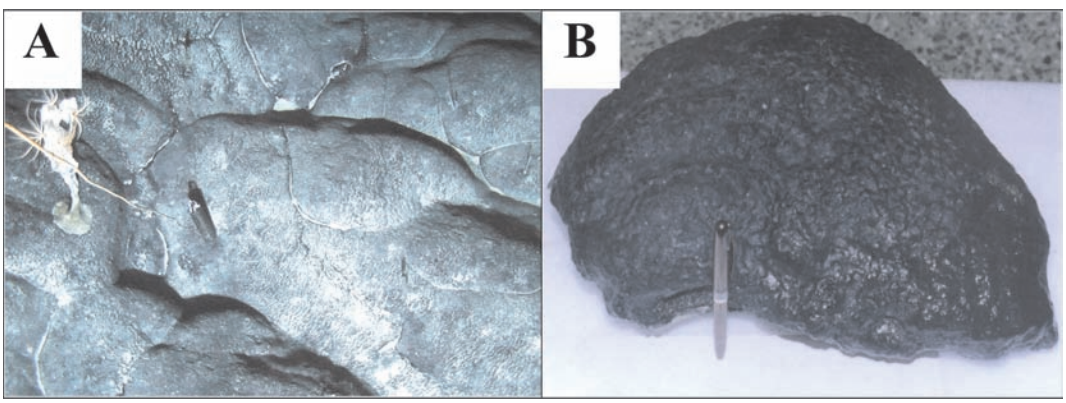
Figure 1: Ferromanganese nodules (dark rounded objects) spread over the seabed sediment (lighter tone area of the photographs). The diameters of nodules in the photographs range between 1 and 6 cm. (A) Photographed during TV-Sledge operation in the Central Pacific at a water depth of 4800 m (Courtesy: D. Tougalesov). The photograph covers a seafloor area of 1.2 $m^2$ and the approximate abundance of nodules is >20 kg/$m^2$, (B) Photographed during camera fitted free-fall grab operation in the Central Indian Ocean at a water depth of 5100 m (Source: NIO's Photo-gallery). The photograph covers a seafloor area of 0.7 $m^2$ and the approximate abundance is 5 kg/$m^2$.




(Moore and Vogt, 1976). Marine ferromanganese deposits also contain variable amounts of fine-grained land-derived silicate detritus that settled through the water column contributing to layers accumulated over a long period of time. In general, the hydrogenous component records the past ocean chemical evolution and the latter reflects the erosion trends in the surrounding landmass. However, the isotopic compositions of both these phases also provide clues for continental weathering history.

A notable publication by Segl et al. (1984) revealed that the FMCs can be faithful repositories of physicochemical conditions of the palaeo-oceans in which they originated. This potential of FMCs mostly lies in the fact that they accrete extremely slowly (1–10 mm/myr: Abouchami et al., 1997; Banakar and Borole, 1991; Segl et al., 1984) through accumulation of molecular-layer-by-molecular-layer and are normally free from diagenetic alterations. There are some exceptions particularly from the Pacific, wherein very thick (very old) FMCs have had their older layers phosphatized through diagenetic processes (e.g., Koschinsky et al., 1997). The last 20 million years of geological history of Himalayan

Figure 2: Cobalt enriched seamount ferromanganese crusts. (A) TV-Sledge photograph showing ferromanganese crust covering Magellan Seamount in Pacific at water depth of 2200 m (Courtsey of D. Tougalesov), (B) Photograph of a sample dredged from the Afanasiy-Nikitin seamount in the eastern equatorial Indian Ocean from water depth of ~2000 m (Banakar et al., 2003. A. A. Sidorenko Cruise-65 Report).



uplift has been traced through accumulation pulses of silicate detritus characterized by Nd–Sr isotopic composition in a FMC from the Central Indian Ocean (Banakar and Hein, 2000; Banakar et al., 2003), while long-term deepwater circulation changes have been reconstructed from isotopic composition of Pacific seamount FMCs (e.g., Segl et al., 1984; Hein et al., 1992; Frank et al., 1999 and references therein).

Even after 150 years of discovery of the FMNs, the exact mechanism that maintains those higher-density nodules resting on the surface of lower-density peneliquid sediment layer (see Figure 1) through thousands of years is still a mystery. It is noteworthy that the accretion rate of FMNs is three orders of magnitude slower than the accumulation rate of sediment on the seafloor. However, a combination of processes and benthic boundary layer properties such as increasing shear strength with increasing depth in sediment, upward forces exerted by burrowing organisms, shaking of the seafloor intermittently by seismic activity, action of bottom currents etc., have been proposed to explain that mystery. In the absence of an upward forcing mechanism, the FMNs would become buried in the sediment rendering them economically unimportant components of the sediment column. Therefore, some force within the upper few centimeter-thick layer of the sediment is essential to keep FMNs on the sediment surface (see Figure 2). For seamount FMCs, such a mechanism is not required as the bottom current activity is adequate enough to keep the sediment from accumulating on seamount slopes and summit, favoring the accumulation of FMCs as continuous slabs attached to rock surfaces.

### *Economic potential of marine ferromanganese deposits*

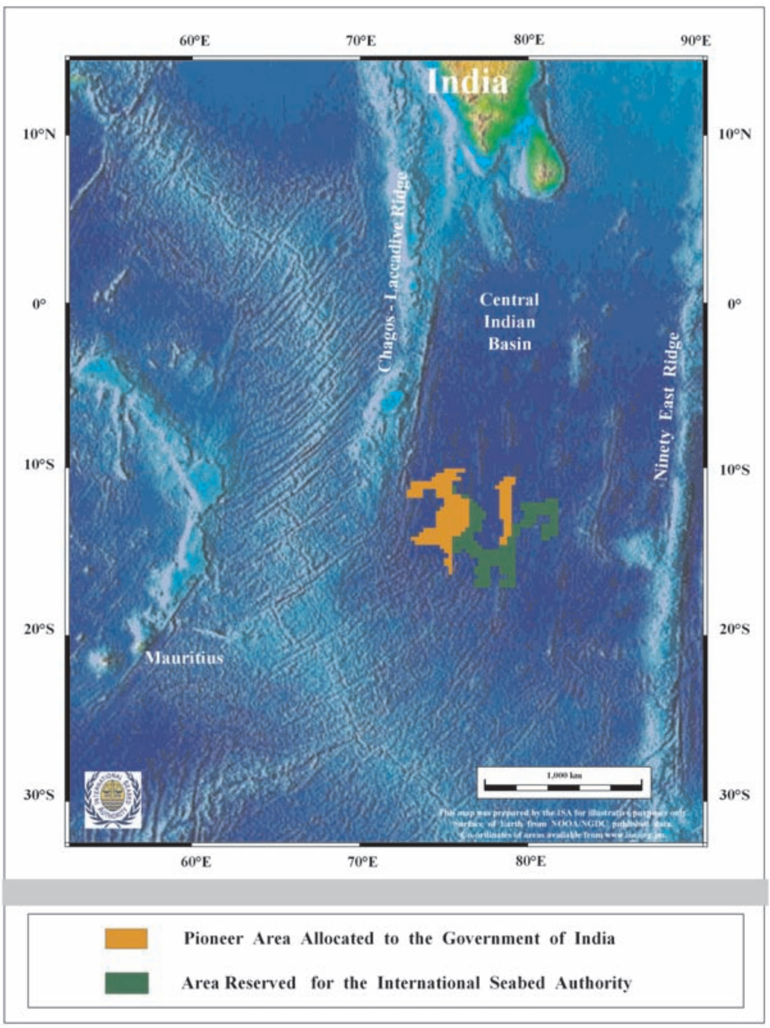
On a global scale, value of a metal generally depends on the overall demand and supply ratio and abundance in nature. In oceanic ferromanganese deposits (FMN and FMC), the major metals are Mn and Fe (~15–30 % and ~10–20 % respectively), while Cu, Ni, and Co (~0.5–1 % each) form the minor metals, and Pt is the most abundant (~200–2000 ppb) amongst the trace level noble metals (see Banakar et al., 2007; Jauhari and Pattan, 2000; Hein et al., 2000 and references therein). For India, Cu, Ni and Co may have strategic importance because of their limited or economically non-workable land-based deposits. The strategic nature of a metal varies from country to country depending upon its local availability, global pricing, and geopolitical scenario.

The Indian Mn (40–63 %) and Fe (50–70 %) ore deposits are estimated to be ~380 million tonnes and ~25 billion tonnes respectively, out of which ~138 million tonnes of Mn ore and ~7 billion tons of Fe ore are considered as reserves (Indian Bureau of Mines, 2008). The 2007–08 domestic consumption of Mn ore was ~2.5 million tones and Fe ore ~80 million tonnes (Indian Bureau of Mines, 2008). Assuming that (a) these rates of consumption approximately represent future long-term Indian needs and (b) all Fe and Mn resources will fall in metallurgical grades due to continuously improving technology, our land-based Mn-deposits would meet domestic requirements for at least the next 150 years and Fe-deposits for 300 years. Further, land-based ores contain 2 to 5 times more Mn and Fe than the oceanic ferromanganese deposits. Therefore, primary metals (Mn and Fe) in oceanic ferromanganese deposits are not at all strategic for India.

The total Indian land reserves of Cu with >1 % metal grade is estimated to be around 650 million tonnes (Indian Bureau of Mines, 2008) containing ~8 million tonnes of metal. The domestic Cu-metal consumption during 2007–08 was ~0.26 million tonnes. That is, Indian land-deposits would support domestic needs of Cu for another three decades. Most of the Indian domestic requirement of Ni is being met by importing over 20,000 tonnes of scrap, alloy, ore concentrate and metal. Although the National Mineral Inventory has accounted for ~190 million tonnes of Ni-ore with >0.5% metal content in Orissa and Bihar, there is no indigenous production of this metal. Mining and processing of these land-based Ni-deposits have not yet been proved economically feasible, hence most of the domestic requirement of the metal is met through import. The reported land-based Co resources are around 45 million tonnes, but the metal content details are not known (see Indian Bureau of Mines, 2008). Further, the reported deposits are not classified as reserves but grouped as resources. The Co-metal demand in India has been rising significantly every year. It was ~150 tons per year in 1987 and reached ~1200 tonnes in 2007-08. These figures are based on the amount of refined metal produced from imported raw material mostly from Democratic Republic of Congo (Cobalt News, 2006).

Thus, Indian land-based Cu-deposits may not be able to sustain growing domestic demand for long, and is also dependent upon imports for Ni and Co. Therefore, these three metals may be strategic for India. The marine ferromanganese minerals with relatively higher percentages of Cu, Ni and Co than that in present land resources (deposits) are therefore the alternative potential ore reserves of strategic importance to India. Further, the enrichment of Pt (Banakar et al., 2007) and Te (Hein et al., 2003) in seamount FMCs may add additional value to these deposits.

Figure 3: Ferromanganese nodule exploration site allocated to India by the International Seabed Authority in 1987 (Brown colored area). Each of the two color coded areas is 150,000 km$^2$ of nearly equal resource value. One area (green) is reserved as a global asset, while the brown seabed area is the exclusive exploration area of India with respect to nodule deposits (www.isba.jm). A similar allocation for seven other pioneer investors has been done in the Clarion–Clipperton region of the Central Pacific. There are no claims for ferromanganese nodules other than that of India in the Indian Ocean.

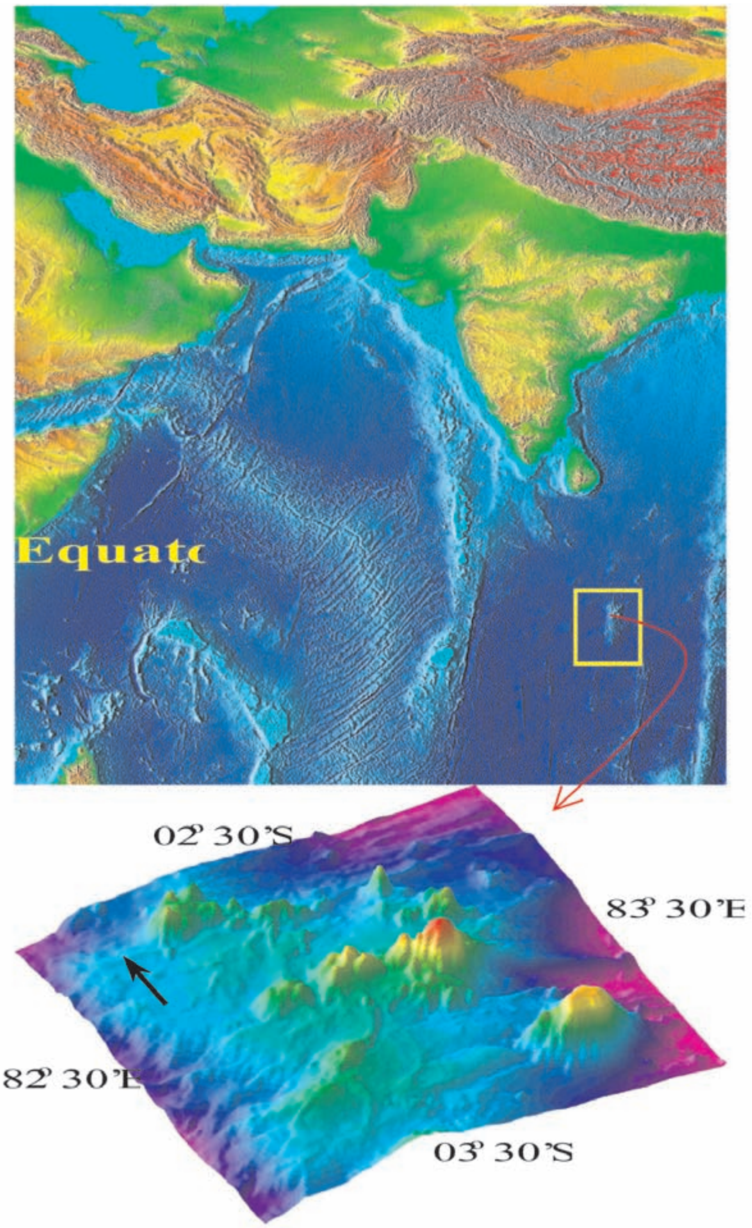



### *India's program for exploring for marine ferromanganese deposits*

The first FMNs collected by Indian researchers was on the R.V. Gaveshani from the Central Indian Ocean in January 1981. This event has led to the formation of the Department of Ocean Development by Government of India. Subsequently, a multi-agency project for exploring FMN deposits was launched under the leadership of National Institute of Oceanography. Four research ships and over fifty dedicated researchers were deployed for the task. As a result of three years of continuous survey covering over 4 million km$^2$, a FMN-rich area was identified and the claim for exclusive exploration rights and potential development of a mine-site in international waters was filed with the International Seabed Authority in January 1984. In August 1987, the International Seabed Authority allocated an area of 150,000 km$^2$ to India for exploration and potential future mining of FMNs in the Indian Ocean (Figure 3) (see articles in 'From first nodule to first mine site', 1988). The allocated exploration site contains ~5 kg of FMNs per square meter of seabed with a combined Cu and Ni content of ~2 %. This would yield a total ore-reserve of ~700 million tonnes that holds within it ~7 million tonnes each of Cu and Ni metals. This quantity of Cu could support our domestic requirement for a little over twenty-five years and Ni for a few thousand years.

The exploration for seamount ferromanganese crusts (FMC) in the Indian Ocean began only recently following a report on enrichment of Co in FMCs found on the Afanasiy-Nikitin Seamounts (ANS) in the Eastern Equatorial Indian Ocean (Banakar et al., 1997). A detailed multibeam bathymetric survey in the ANS region revealed clusters of seamounts at a water-depth ranging between 1.7 to 3 km (Figure 4), with FMCs containing Co metal up to 0.9 % and Pt up to 1 ppm (Banakar et al., 2007; Rajani et al., 2005). The National Institute of Oceanography launched a major project to explore seamounts in the equatorial and northern Indian Ocean for Co-enriched FMCs. The National Geophysical Research Institute and National Center for Antarctic and Ocean Research are other partners in this effort having funding support from the Ministry of Earth Sciences. Initial work indicated the occurrence of FMCs in the ANS region with an average Co content of ~0.65 %, Pt ~0.5 ppm and Ce 0.22 % (Banakar et al., 2007; Rajani et al., 2005). In addition to the above metals, the oceanic ferromanganese deposits enrich rare earth elements by one to two orders of magnitude above the average continental crust composition (DeCarlo et al., 1992; Elderfield et al., 1981; Nath et

Figure 4: The first cobalt-rich ferromanganese crusts in the Central Indian Ocean were recovered from the Afansiy-Nikitin seamounts (shown in box) in 1994. This seamount region is punctuated with clusters of smaller volcanic seamounts rising up to 1.7 km water depth. The first sample was from the top of a mount at 1700 m water depth (red colored portion of the seamount shown in 3D inset). This area is under detailed study for cobalt-rich ferromanganese crusts. The 3D map of the northern part of the Afanasiy-Nikitin Seamount region was prepared from multibeam bathymetric surveys conducted in 2005 on board the A. B. Boris Petrov (Source: Banakar et al., 2007).




al., 1992; Jauhari and Pattan, 2000). Interestingly, the ANS deposits contain very high Ce (up to 0.37 %, average ~0.22 %, see Rajani et al., 2005), which appears to be the highest Ce-enrichment known so far for oceanic ferromanganese deposits.

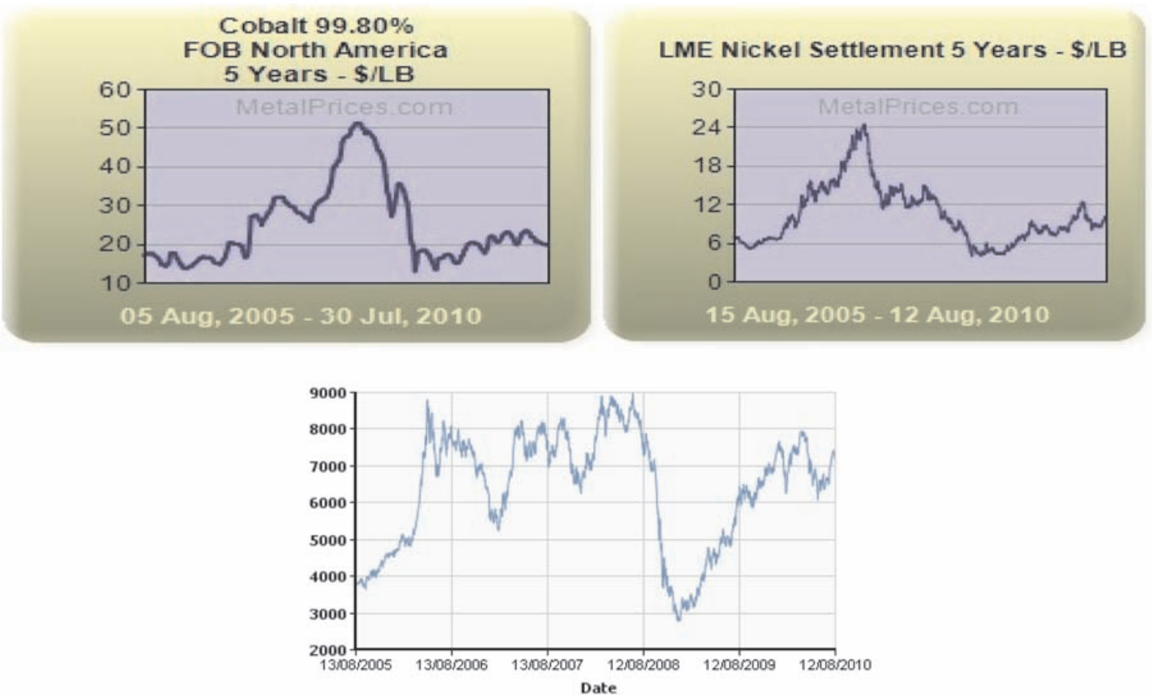
***Preliminary economics of ferromanganese deposits***

Although in international metal markets, the prices of Cu, Ni and Co have shown rapid fluctuations from month-to-month and year-to-year, the last few year averages have provided indications of demand and supply. In the London Metal Market (see www.metalprices.com), the Cu price has fluctuated between 1.4 and 4 $/lb in the last five years with an average of ~2.5 $/lb, Ni between 6 and 24 $/lb with an average of ~12 $/lb, and Co fluctuated between 12 and 50 $/lb with an average of ~30 $/lb (see Figure 5). Applying these values to the Indian lease area in the Central Indian Ocean, that is estimated to contain about 7 million tonnes each of Cu and Ni and ~0.7 million tonnes of Co, would translate approximately to ~175, ~800, and ~200 billion rupees respectively, yielding a total three-metal resource value of roughly around Rs. 1100 billion or ~US $ 24 billion at the present exchange rate. On the other hand, yet unknown deposits of seamount FMCs might contain several billion worth of Co as this metal is ten times more expensive than Cu and three times more expensive than Ni. FMCs contain 6 times more Co than FMNs.

The presence of Pt in considerable concentrations (0.5–1 g/ton, i.e., 0.5–1 ppm) in FMCs would increase its resource value significantly if a viable extractive metallurgical process could be developed. For every tonne of FMC having 1 g of Pt, the value enhancement of the FMC would be Rs. 2000 per ton of crusts on the basis of last 5-year average market rate of Pt (~1500 US $/TroyOz: see London Metal Exchange, Platinum News, 7 April 2010). Thus, it has become necessary to know the occurrence of marine ferromanganese deposits in waters surrounding India in both national (EEZ) and international jurisdictions. Accurate technology and quantitative economic feasibility studies of these deposits (both mining and metallurgy) are essential to make decisions on deep-sea mining by any pioneer investor country having an International Seabed Authority registered lease area.

A tentative technology and -economic study by Glasby (1983) suggested that, in order to make FMN mining a profitable proposition, there was a need to lift a minimum of 11,000 tonnes of FMNs per day from the water depths of over 4 km using a single mining vessel, i.e., ~4 million tonnes of FMNs per year. There are no published reports yet on the availability of deep-sea mining systems to achieve such targets. However, there are ongoing efforts to develop deep-sea nodule mining systems although results have not been published. The growing international opinion is that the seamount FMC deposits may become potential targets of deep-sea mining within the next decades due to their

Figure 5: Last five-year price variations of three strategic metals (Indian context) in the international metal market (Source: www.metalprice.com), which were found enriched in marine ferromanganese deposits. The y-axis in copper-panel indicates price in US $ per tonne.




enrichment of high-tech metals such as Co, Pt, Te etc., which have next generation usage in computer chips, photovoltaic solar cells, catalytic converters, high-strength super-alloys, superconductors etc. (Hein et al., 2010).

## Acknowledgements

The author wishes to thank Raghuram Murtugudde for inviting him to contribute this article. Ministry of Earth Sciences (formerly the Department of Ocean Development) funded the Indian deep-sea ferromanganese mineral exploration efforts. S. Z. Qasim and H. N. Siddiqui seeded the Indian ferromanganese nodule program, which was further nurtured by R. R. Nair with the support of the polymetallic nodule project team. The Indian seamount cobalt-enriched ferromanganese crust program is the outcome of the author's efforts, which is being supported by the Ministry of Earth Sciences. The constructive review and valuable suggestions by Jim Hein, USGS, helped to improve this manuscript.

Received 27 October 2010.

References

1. Abouchami, W., Goldstein, S. L., Galer, S. J. G. et al., 1997. Secular changes of Pb and Nd in Central Pacific seawater recorded by a Fe–Mn crust. *Geochimica et Cosmochimica Acta*, 61, 3957–3974.
2. Banakar, V. K. and Borole, D. V. 1991. Depth profiles of 230Thexcess, transition metals, and mineralogy of ferromanganese crusts of the Central Indian Ocean and implications for paleoceanographic influence on crust genesis. *Chemical Geology* (Isot. Geosci. Sectt.), 94, 33–44.
3. Banakar, V. K. and Hein, J. R., 2000. Growth response of a deep-water ferromanganese crust to evolution of the Neogene Indian Ocean. *Marine Geology, 162*, 529–540.
4. Banakar, V. K., Pattan, J. N., Mudholkar, A. V., 1997. Paleoceanographic conditions during formation of a ferromanganese crust from the Afanasiy-Nikitin Seamounts, north-central Indian Ocean: Geochemical evidences. *Marine Geology*, 136, 299–315.
5. Banakar, V. K., Galy, A., Sukumaran, N. P., Parthiban, G., Volvaiker, A. Y., 2003. Himalayan sedimentary pulses recorded by silicate detritus within a ferromanganese crust from the Central Indian Ocean. *Earth and Planetary Science Letters*, 205, 337–348.
6. Banakar, V. K., Hein, J. R., Rajani, R. P., Chodankar, A. R., 2007. Platinum group elements and gold in ferromanganese crusts from Afanasiy-Nikitin Seamount, equatorial Indian Ocean. *Journal of earth System Science*, 116, 3–13.
7. Cobalt News-July 2006, Published by Cobalt Development Institute, UK.
8. DeCarlo, E. H., 1991. Paleoceanographic implications of rare earth element variability within a Fe–Mn crust from the central Pacific Ocean. *Marine Geology*, 98, 449–467.
9. Elderfield, H., Hawkesworth, C. J., Greaves, M. J., Calvert, S. E., 1981. Rare earth element geochemistry of oceanic ferromanganese nodules and associated sediments. *Geochimica et Cosmochimica Acta*, 45, 513–526.
10. Frank, M., O'Nions, R. K., Hein, J. R., Banakar, V. K., 1999. 60 Myr record of major element and Pb–Nd isotopes

from hydrogenous ferromanganese crusts: Reconstruction of seawater paleochemistry. *Geochimica et Cosmochimica Acta*, 63, 1689–1708.
11. Glasby, G. P. (Editor), 1977. Marine manganese deposits. *Oceanography Series–15*, Elsevier, p. 523.
12. Glasby, G. P. 1983. Economics of manganese nodule mining. *Marine Mining*, 4, 73–77.
13. Halbach, P., Manheim, F. T., Otten, P., 1982. Cobalt-rich ferromanganese deposits in the marginal seamount regions of the central Pacific-results of the Midpac 81. *Erzmetall*, 35, 447–453.
14. Hein, J. R., Bohrson, W. A., Schulz, M. S. et al., 1992. Variation in the fine-scale composition of a central Pacific ferromanganese crust: Plaeoceanographic implications. *Paleoceanography*, 7, 63–77.
15. Hein, J. R., Morgenson, L. A., Clague, D. A., Koski, R. A., 1987. Cobalt-rich ferromanganese crusts from the EEZ of the United States and nodules from the oceanic Pacific. In: Scholl, D. W. et al. (Eds.), Geology and resource potential of continental margin of western north America and adjacent ocean basins. Circum-Pacific Council for Energy and Mineral Resources earth science Series-6, Department of Energy, USA, 753–771.
16. Hein, J. R., Koschinsky, A., Bau, M. et al., 2000. Cobalt-rich ferromanganese crusts in the Pacific. In: D. S. Cronan (Ed.) *Handbook of marine mineral deposits*. CRC Press, pp. 239–279.
17. Hein, J. R., Conrad, T. A., Staudigel, H., 2010. Seamount mineral deposits: A source of rare metals for high-tech industry. *Oceanography*, 23, 184–189.
18. Indian Bureau of Mines. 2010. Indian Mineral Yearbook-2008. IBM Press, Nagpur, p. 617.
19. Jauhari, P., Pattan, J. N., 2000. Ferromanganese nodules from the Central Indian Ocean. In: D. S. Cronan (Ed.) *Handbook of marine mineral deposits*. CRC Press, pp. 171–196.
20. Koschinsky, A., Stascheit, A. M., Bau, M., Halbach, P., 1997. Effects of phosphotization on the geochemical and mineralogical composition of marine ferromanganese crusts. *Geochim. Cosmochim. Acta*, 61, 4079–4094.
21. Manheim, F. T., 1986. Marine cobalt resources. *Science*, 232, 600–608.
22. Mero, J. L., 1965. The mineral resources of the sea. In: *Oceanography Series 1*, Elsevier, 182–219.
23. Moore, W. S., Vogt, P. R., 1976. Hydrothermal manganese crusts from two sites near Galapagos spreading axis. *Earth and Planetary Science Letters*, 29, 349–356.
24. Nath, B. N., Balram, V., Sudhakar, M., Pluger, W. L., 1992. Rare earth element geochemistry of ferromanganese deposits from the Indian Ocean. *Marine Chemistry*, 38, 185–196.
25. Qasim, S. Z., Nair, R. R. (Editors), 1988. First nodule to first mine site: an account of the polymetallic nodule project. Dept. Ocean. Dev. and Nat. Instt. Oceanogr., p. 50.
26. Rajani, R. P., Banakar, V. K., Parthiban, G., Mudholkar, A. V., 2005. Compositional variation and genesis of ferromanganese crusts of the Afanasiy-Nikitin Seamount, Equatorial Indian Ocean. *Journal of Earth System Science*, 114, 51–61.
27. Segl, M. A., Mangini, G., Bonani, G., Hoffman, H. J. et al., 1984. 10Be dating of a manganese crust from central north Pacific and implication for ocean paleocirculation. *Nature*, 309, 540–543.

**Virupaxa K. Banakar** Born in Kotumachigi village of Gadag District (Karnatak) on 1 July 1956. Primary and secondary education was completed in Kotumachigi. Graduated in Applied Geology from Karnatak University in 1981. Joined National Institute of Oceanography, Goa, as Scientist-B in 1982 and presently working as Scientist-G. Research interests are marine mineral deposits and paleoclimate reconstructions. Initially worked for polymetallic nodule program that gained pioneer status for India from the International Seabed Authority. Obtained Ph. D. in 1989 for thesis related to geochemistry and radiochemistry of ferromanganese nodules and crusts from the Central Indian Ocean. Discovered the cobalt-enriched ferromanganese crusts in Equatorial Indian Ocean and leading a major project on exploration of these deposits in international waters. Elected as St. John's Visiting Scholar for year 2002 by the University Cambridge, UK; Raman Visiting Scientist at Hokkaido University, Japan in year 2001; Senior Visiting Scientist of JSPS at Kochi University, Japan in 2007; and Visiting Researcher at the University of Hamburg in 1989. Worked as Editorial Board member of Indian Journal of Marine Sciences from 2005–08.